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(54) Title: CRYSTAL OSCILLATOR
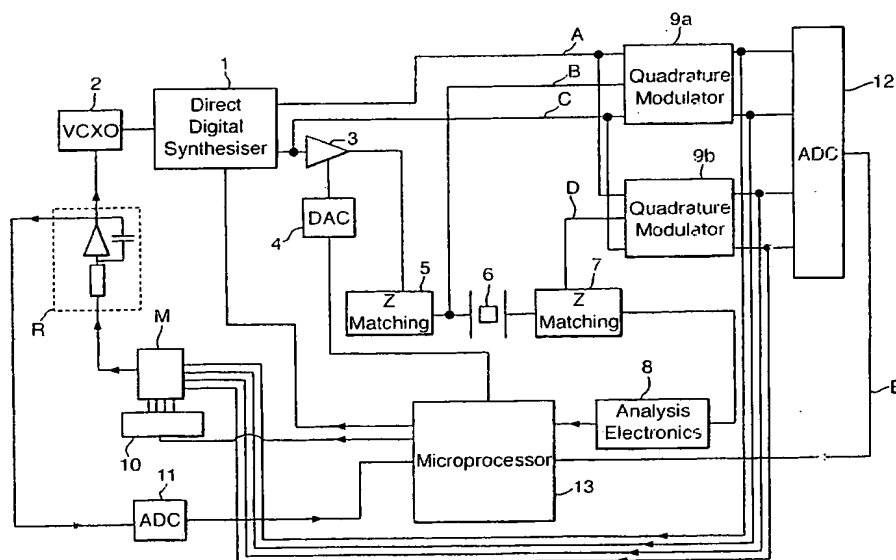
(57) Abstract: An apparatus for oscillating a surface is described. The apparatus comprises an oscillator circuit having: a) a piezo-electric crystal connected to the surface; b) a variable frequency generator for generating a driving signal which is supplied to the crystal to cause the crystal to oscillate, thereby causing the surface to oscillate; and, c) an analyser for monitoring the phase shift between the voltage across the crystal and the current flowing through it and, in response generating an adjustment signal which relates to the difference between the oscillation frequency and a resonant frequency of the crystal, the variable frequency generator being responsive to the adjustment signal to vary the frequency of the driving signal to cause the crystal to oscillate at the resonant frequency.

# CRYSTAL OSCILLATOR

This invention relates to a crystal oscillator
circuit for example, for use in sensors and a method of
operation in which the crystal is caused to oscillate at
a chosen resonant frequency, irrespective of changes in
that frequency.   The invention finds particular utility
under conditions where high drive  power and external
influences cause unpredictable changes in the resonant
frequency.

In conventional applications of quartz crystal
oscillators, such as timing and frequency control, the
quartz crystal is connected in a resonant circuit and
maintains a highly stable frequency of operation since,
amongst other reasons, a low driving voltage is used.  In
these applications, the control of the driving voltage is
not as important as the frequency of oscillation and
maintaining the driving voltage at a low level avoids
heating the crystal.

Quartz and other piezo-electric oscillators are
widely used in sensing applications; for example, in the
sensing of temperature, pressure, mass and viscosity.  In
such applications there is a need to ensure that the
frequency stays on resonance, and methods for achieving
this are known.  They include temperature stabilisation,
free-running oscillator circuits, and phase shifting
networks.  In all these cases the oscillator is operating
at a fixed low power level and in its linear range

However, there are applications, for example sensor
applications, of quartz crystals where the driving power
is required to be varied over a much wider range,
including power levels which drive the crystal into its
non-linear mode of operation.  For example, the quartz
crystal may be used as a motional transducer.  Such an
application is rupture event scanning (REVS™) which is
described in WO01/02857.  In this application, the
driving voltages are typically up to 20 volts peak to

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peak.  It is well known that as the driving voltage
increases, the resonant frequency of the crystal changes.
This is due to a number of effects, such as irreversible
voltage induced changes in the quartz structure caused by
the nonlinear response of the quartz crystal to high
voltages and temperature dependence of the crystal's
resonant frequencies caused by the heating of the crystal
at high power levels.

In conventional oscillator applications, the
oscillator selects the strongest mode. Spurious modes
exist in crystals whose power versus frequency
characteristics may approach or cross that of the
resonance at higher power.  These interactions can change
the resonant response of the crystal.  Spurious modes
close to the resonance which are normally of low
intensity may have a steep frequency versus temperature
characteristic.  At a certain temperature, the frequency
of an unwanted mode may coincide with the oscillator
frequency.  Both these effects can cause a "mode hop" or
abrupt change in the frequency of the oscillator.

Furthermore, in many sensors it is desirable to
operate at a resonant overtone of the crystal, because
sensitivity of some parameters is increased at higher
frequencies.   However as the overtone frequency
increases, the density of spurious modes also increases,
and the probability of mode-hopping increases.   Unwanted
modes can be controlled by proper design and fabrication
methods for low power applications; however, as the power
level increases this becomes increasingly difficult.

In the REVS™ process, the power level may typically
be varied from zero to 250mW, and this must be done in a
controlled way while maintaining the oscillation at
resonance.  Any deviation from the resonance will cause
the amplitude of the mechanical motion of the crystal to
decrease.  Since identification of a rupture event is
dependent on the control of mechanical motion such
deviations cannot be tolerated.

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The problems described below are exacerbated in
rupture event scanning where the crystal is in contact
with a dissipative fluid. As the amplitude increases
non-linear visco-elastic effects change the frictional

5    forces on the crystal in an unpredictable way.
Dissipative losses in the fluid may also cause heating of
the crystal. These effects can cause changes in the
resonant frequency of the crystal as the power is
increased.

10    Thus, in REVS™ there is a need to have a frequency
control system which actively drives the crystal always
on resonance, and which can follow unpredictable changes
in the resonant frequency due to thermal and non-linear
effects, while maintaining control over the drive power

15    supplied.
In accordance with one aspect of the present
invention, there is provided an apparatus for oscillating
a surface, the apparatus comprising an oscillator circuit
having:

20    a)    a piezoelectric crystal connected to the
surface;

b)    a variable frequency generator for generating a
driving signal which is supplied to the crystal
to cause the crystal to oscillate, thereby

25    causing the surface to oscillate; and,

c)    an analyser for monitoring the phase shift
between the voltage across the crystal and the
current flowing through it and, in response,
generating an adjustment signal which relates

30    to the difference between the oscillation
frequency and a resonant frequency of the
crystal, the variable frequency generator being
responsive to the adjustment signal to vary the
frequency of the driving signal to cause the

35    crystal to oscillate at the resonant frequency.
In accordance with a second aspect of the present
invention there is provided a method for oscillating a

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surface, the method comprising:

   a)  producing a driving signal that causes a
       piezoelectric crystal connected to the surface
       to oscillate thereby causing the surface to
       oscillate;

   b)  monitoring the phase shift between the voltage
       across the crystal and the current flowing
       through it and, in response, generating an
       adjustment signal which relates to the
       difference between the oscillation frequency
       and a resonant frequency of the crystal; and,

   c)  varying the frequency of the driving signal in
       accordance with the adjustment signal such that
       the crystal oscillates at the resonant
       frequency.

Hence, the invention provides an apparatus and
method for oscillating a surface by oscillating a
piezoelectric crystal connected to the surface such that
the crystal oscillates at one of its resonant
frequencies, irrespective of changes in that frequency.

Typically, the variable frequency generator
comprises a frequency synthesiser which is supplied by a
reference frequency. This reference frequency may be
temperature stabilised in the form of an oven control
crystal oscillator or alternatively may be a voltage
controlled reference in the form of a voltage controlled
crystal oscillator.

In a preferred embodiment, the variable frequency
generator additionally generates a quadrature signal that
is shifted in phase by 90° from the driving signal. In
this event, the analyser typically comprises two
quadrature modulators, one receiving the driving signal,
the quadrature signal and a signal representing the
voltage across the crystal and the other receiving the
driving signal, the quadrature signal and a signal
representing the current flowing through the crystal.
Typically, the adjustment signal is related to the phase

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shift between the voltage and the current.

The adjustment signal may control the operation of
the frequency synthesiser directly therefore changing the
frequency of the driving signal or alternatively the
5    adjustment signal may control the frequency of
oscillation of the voltage controlled crystal oscillator,
if present.

Preferably, a voltage controlled amplifier is used
to control the amplitude of oscillation of the crystal.
10    An embodiment of the invention will now be described
with reference to the accompanying drawings in which:

Figure 1 shows, schematically, apparatus for
performing the invention;

Figure 2 shows a detailed view of part of Figure 1;
15    and,

Figure 3 shows an alternative implementation for
part of Figure 1.

Figure 1 shows a high resolution frequency
synthesiser 1 which produces a driving signal, on line C,
20    that is supplied to a voltage controlled amplifier 3 and
to quadrature modulators 9a, 9b.  The frequency
synthesiser 1 also produces a quadrature signal, on line
A, that is supplied to the quadrature modulators 9a, 9b.
A voltage controlled crystal oscillator (VCXO) 2 is used
25    as a reference frequency for the frequency synthesiser 1.
The signal produced by the VCXO 2 is proportionally
converted by the frequency synthesiser 1 into the
frequency at which the driving signal and quadrature
signal output by the frequency synthesiser 1 oscillate.
30    Such frequency synthesisers are well known in the
art.  The AD9854 made by Analog Devices is a suitable
example.  This digitally synthesises a precision
sinusoidal signal at a programmable frequency using a
high frequency reference oscillator.  In the example, the
35    synthesis of a typical 14.2MHz signal suitable for use in
REVS™ can be achieved using a 20MHz VCXO reference.  The
typical stability of the frequency synthesiser output is

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<0.1Hz.

The amplitude of the driving signal is controlled by
a voltage controlled amplifier (VCA) 3, the gain of which
is under control of microprocessor 13 which causes
5      digital to analogue converter (DAC) 4 to supply an
appropriate control signal to VCA 3. The output from VCA
3 drives a piezoelectric crystal 6 via an impedance
matching network 5. The impedance matching network 5
ensures that the output from the VCA 3 is matched in
10     impedance with the crystal 6 such that energy is
efficiently coupled into the crystal 6.

The crystal 6 is also connected to quadrature
modulator 9a in order to supply this with a signal
representing the voltage across the crystal 6.

15     The crystal 6 is connected to a second impedance
matching network 7 which couples the signal energy from
the crystal 6 into a set of analysis electronics 8 that
are connected to the microprocessor 13. The analysis
electronics 8 perform the signal extraction required for
20     rupture event scanning.

The network 5 is configured such that it presents a
high impedance to frequencies other than those at or near
the drive frequency. Conversely, the network 7 is
configured such that it presents a high impedance to
25     frequencies other than those at or near the detection
frequency. Thus, network 7 provides a virtual ground to
the drive frequency, and the signal in line B can be used
as an input to quadrature modulator 9a.

The second impedance matching network 7 also
30     provides a signal representing the current flowing
through the crystal 6 to quadrature modulator 9b.

The signals representing the voltage across the
crystal 6 and the current flowing through it, present on
lines B and D respectively, are both shifted in phase
35     with respect to the driving signal from frequency
synthesiser 1, due to the reactive impedance
characteristics of the circuit and the configuration of

the hardware.

At resonance, the impedance of the crystal 6 is at a
minimum and is entirely resistive in nature. The
resistive impedance is determined by the motional
5    resistance of the crystal 6 and the viscous energy
dissipation in the fluid in contact with the crystal. A
typical value for this in a rupture event scanning
application is 200 ohms. Since the impedance of the
crystal is resistive at resonance, it is possible to
10   determine that the crystal is oscillating at a resonant
frequency by measuring the phase shift between the
voltage developed across the crystal 6 and the current
flowing through it. At resonance, this phase shift will
be zero. In effect, the phase shift provides an
15   indication of the difference between the resonant
frequency and the actual frequency of oscillation.

It is an essential requirement for an application
such as REVS™ that the power delivered to the crystal is
controlled smoothly and preferably linearly in response
20   to the gain of amplifier 3. Phase shifts between current
and voltage at the crystal cause uncontrolled deviations
in the amplitude of oscillation and thus, must be
minimised as much as possible. This is carried out by a
phase modulator array M and DAC (10).

25   As previously described, a signal representing the
voltage across the crystal 6 is supplied to quadrature
modulator 9a and a signal representing current flowing
through the crystal 6 is supplied to quadrature modulator
9b. These quadrature modulators 9a, 9b mix the
30   respective voltage and current signals with the driving
and quadrature signals produced by the frequency
synthesiser 1 to produce four output signals, two from
quadrature modulator 9a and two from quadrature modulator
9b.

35   Quadrature modulators are well known components and
the output signals from quadrature modulator 9a represent
the real and imaginary components of the voltage across

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the crystal 6 and the outputs from quadrature modulator
9b represent the real and imaginary components of the
current flowing through the crystal 6.  These four
signals are supplied to an analogue to digital converter
5      (ADC) 12 which supplies digital representations of these
to microprocessor 13, via four line bus E.  This
information can be used to provide a true driver power
co-ordinate in the rupture event scanning analysis.

       The compensation signal used for frequency
10     adjustment is provided by the modulator array M and DAC
10.  Modulator array M is an array of potentiometers
controlled by DAC 10.  DAC 10 applies weighting signals
to the voltage and current components outputs from
quadrature modulators 9a, 9b according to coefficients
15     that are set via an input from microprocessor 13.  This
is shown in more detail in Figure 2.  Alternatively,
modulator array M and DAC 10 can be combined in an array
of digitally controlled potentiometers.

       The weighting coefficients applied by the DAC 10 are
20     such that if a purely resistive load is placed in the
position of the crystal 6, then when the weighted signals
are added, the resulting signal is restored to being in
phase with the reference signal of frequency synthesiser
1.

25        The coefficients can be determined by calibrating
the circuit with a purely resistive load and once
established can be used for a specified  drive frequency,
or circuit configuration.

       As described earlier, when driving at high powers
30     with a dissipative load the resonance frequency of the
oscillator may be susceptible to drift and unpredictable
changes.  Any such changes will bring about an additional
phase shift at the output of the modulator array.

       This phase shifted signal  is integrated over time
35     by the integrating regulator R, the output of which
drives VCXO 2.  Thus, as the resonant frequency of the
crystal drifts, this will cause the phase to shift,

producing a compensating change in the output of the
modulator array M, which then corrects the drive
frequency of the frequency synthesiser 1. The phase
shift output of the regulator R can also be connected to
5    the microprocessor 13, for further analysis.

Therefore, the frequency of the driving and
quadrature signals produced by frequency synthesiser 1
can be caused to follow the changes in the resonant
frequency of the crystal 6 by altering the frequency of
10   oscillation of VCXO 2 directly via the output of the DAC
10.

Although the method described above is analogue, it
is also possible to use digital or hybrid methods to
achieve the same effect.

15   In a digital implementation, the phase shift between
the four outputs of quadrature modulators 9a, 9b,
representing the voltage across crystal 6 and the current
flowing through it, is calculated by software running on
microprocessor 13. This operates on the digital
20   representations of the real and imaginary components of
the voltage across crystal 6 and the current flowing
through it received from ADC 12, via bus E, and thereby
adjusting the operation of frequency synthesiser 1.

A digital implementation is shown in Figure 1 where
25   the four digitised signals (bus E) from ADC 12 (being
digital representations of the outputs from quadrature
modulators 9a, 9b) are read and processed by
microprocessor 13, and the phase difference between the
voltage across crystal 6 and the current flowing through
30   it is calculated. The microprocessor 13 then integrates
the phase difference and calculates the digital input
signal necessary to adjust the frequency of oscillation
of the frequency synthesiser 1 to follow the resonant
frequency of the crystal 6. If the VCXO 2 is absent in
35   this arrangement, the frequency synthesiser 1 must have a
high resolution, typically <0.1Hz, and the ability to
smoothly change frequency. Suitable devices are

commercially available.

Figure 3 shows an alternative arrangement in which quadrature modulators 9a, 9b supply digital signals directly to microprocessor 13.

5      The two operations of phase calculation, and frequency control can each be either digital or analogue. There may be advantages in operation of such a hybrid system.  For example, it is quite demanding to carry out the phase calculation and integration digitally in real

10     time, so an analogue operation may produce more effective control, combined with a digital drive to frequency synthesiser 1.

As such, by monitoring the voltage across the crystal 6 and current flowing through it, it is possible

15     for the frequency of the driving signal supplied to it by frequency synthesiser 1 to be adjusted such that the crystal 6 is always forced to oscillate at the resonant frequency, irrespective of variations in that frequency.

With respect to a rupture event scanning

20     application, the crystal 6 is desired to oscillate at one of its series resonant frequencies.  Since the characteristics of each crystal are unique in their own right and depend on the characteristics of the fluid with which it is in contact, the crystal is first prescanned

25     whilst in contact with the fluid before performing the analysis in order to determine its resonant frequency.

The frequency of the driving signal is first increased in, for example, 5kHz steps from a value close to the nominal resonant frequency whilst maintaining the

30     amplitude of the driving signal at a low amplitude.  The voltage across the crystal 6 and the current flowing through it are measured at each step.  The phase shift between these is then used to determine an estimate of the resonant frequency.  When close to resonance the

35     variation of phase shift with frequency is linear. Therefore, the phase versus frequency data can be extrapolated to zero phase and the resonant frequency

approximately determined.

The frequency of the driving signal is then
increased in smaller steps, for example 50Hz, in a
smaller range around the resonant frequency. The phase
5    difference is again measured, and then the resonant
frequency can be determined precisely by interpolation.
Alternatively, the coarse data can be fitted to the known
variation of phase with frequency, and the resonant
frequency determined directly.

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CLAIMS

1.    An apparatus for oscillating a surface, the
apparatus comprising an oscillator circuit having:

5              a)    a piezoelectric crystal connected to the
                     surface;

               b)    a variable frequency generator for generating a
                     driving signal which is supplied to the crystal
                     to cause the crystal to oscillate, thereby
10                   causing the surface to oscillate; and,

               c)    an analyser for monitoring the phase shift
                     between the voltage across the crystal and the
                     current flowing through it and, in response,
                     generating an adjustment signal which relates
15                   to the difference between the oscillation
                     frequency and a resonant frequency of the
                     crystal, the variable frequency generator being
                     responsive to the adjustment signal to vary the
                     frequency of the driving signal to cause the
20                   crystal to oscillate at the resonant frequency.

2.    Apparatus according to claim 1, wherein the variable
frequency generator comprises a frequency synthesizer.

3.    Apparatus according to claim 2, wherein the
frequency synthesizer is supplied by a reference
25    frequency from an oven controlled crystal oscillator.

4.    Apparatus according to claim 2, wherein the
frequency synthesizer is supplied by a reference
frequency from a voltage controlled crystal oscillator.

5.    Apparatus according to any of the preceding claims,
30    wherein the variable frequency generator additionally
generates a quadrature signal that is shifted in phase by
90° from the driving signal.

6.    Apparatus according to claim 5, wherein the analyser
comprises two quadrature modulators, one receiving the
35    driving signal, the quadrature signal and a signal
representing the voltage across the crystal and the other
receiving the driving signal, the quadrature signal and a

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signal representing the current flowing through the crystal.

7.    Apparatus according to claim 6 when dependent on claim 2, wherein the adjustment signal controls the operation of the frequency synthesiser thereby changing the frequency of the driving signal.

8.    Apparatus according to claim 6 when dependent on claim 4, wherein the adjustment signal controls the frequency of oscillation of the voltage controlled crystal oscillator thereby changing the frequency of the driving signal.

9.    Apparatus according to any of the preceding claims, further comprising a voltage controlled amplifier for controlling the amplitude of oscillation of the crystal.

10.    A method for oscillating a surface, the method comprising:

       a)    producing a driving signal that causes a piezoelectric crystal connected to the surface to oscillate thereby causing the surface to oscillate;

       b)    monitoring the phase shift between the voltage across the crystal and the current flowing through it and, in response, generating an adjustment signal which relates to the difference between the oscillation frequency and a resonant frequency of the crystal; and,

       c)    varying the frequency of the driving signal in accordance with the adjustment signal such that the crystal oscillates at the resonant frequency.

11.    A method according to claim 10, wherein the driving signal is produced by frequency synthesis from a reference frequency.

12.    A method according to claim 11, wherein the reference frequency is temperature stabilised.

13.    A method according to claim 11, wherein the reference frequency is voltage controlled.

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14.   A method according to any of claims 10 to 13,
wherein the voltage across and current flowing through
the crystal are monitored and the adjustment signal is
related to the phase shift between the voltage and

5    current.

15.   A method according to claim 14, wherein a quadrature
signal that is in quadrature with the driving signal is
also produced, the driving signal and quadrature signal
both being mixed with a signal representing the voltage

10   across the crystal and with a signal representing the
current flowing through the crystal.

16.   A method according to any of the preceding claims,
further comprising controlling the amplitude of
oscillation of the crystal.

15   17.   Use of apparatus according to any of claims 1 to 9
for separating from the surface an analyte that has been
immobilised on the surface.

18.   Use of a method according to any of claims 10 to 16
for separating from the surface an analyte that has been
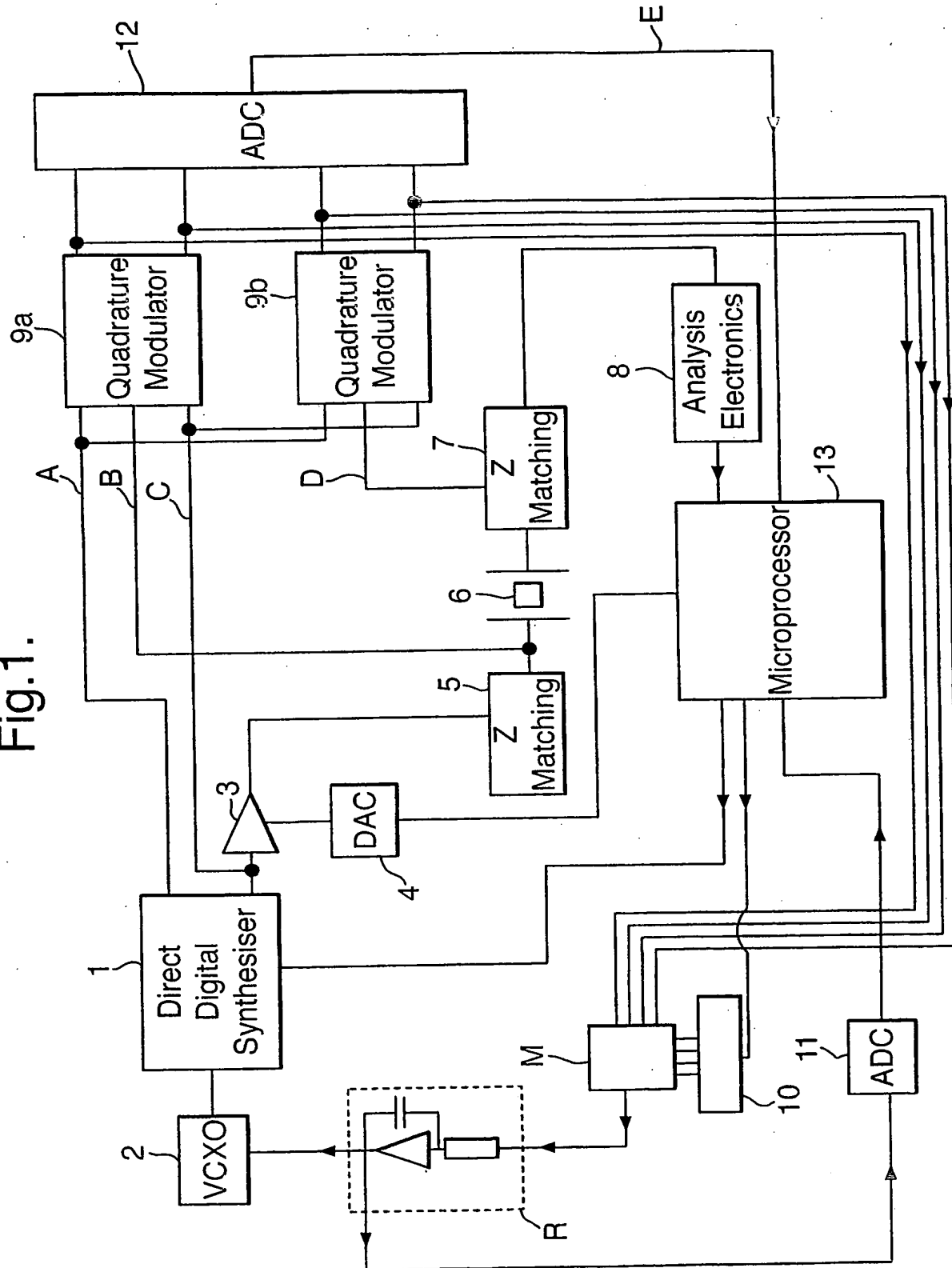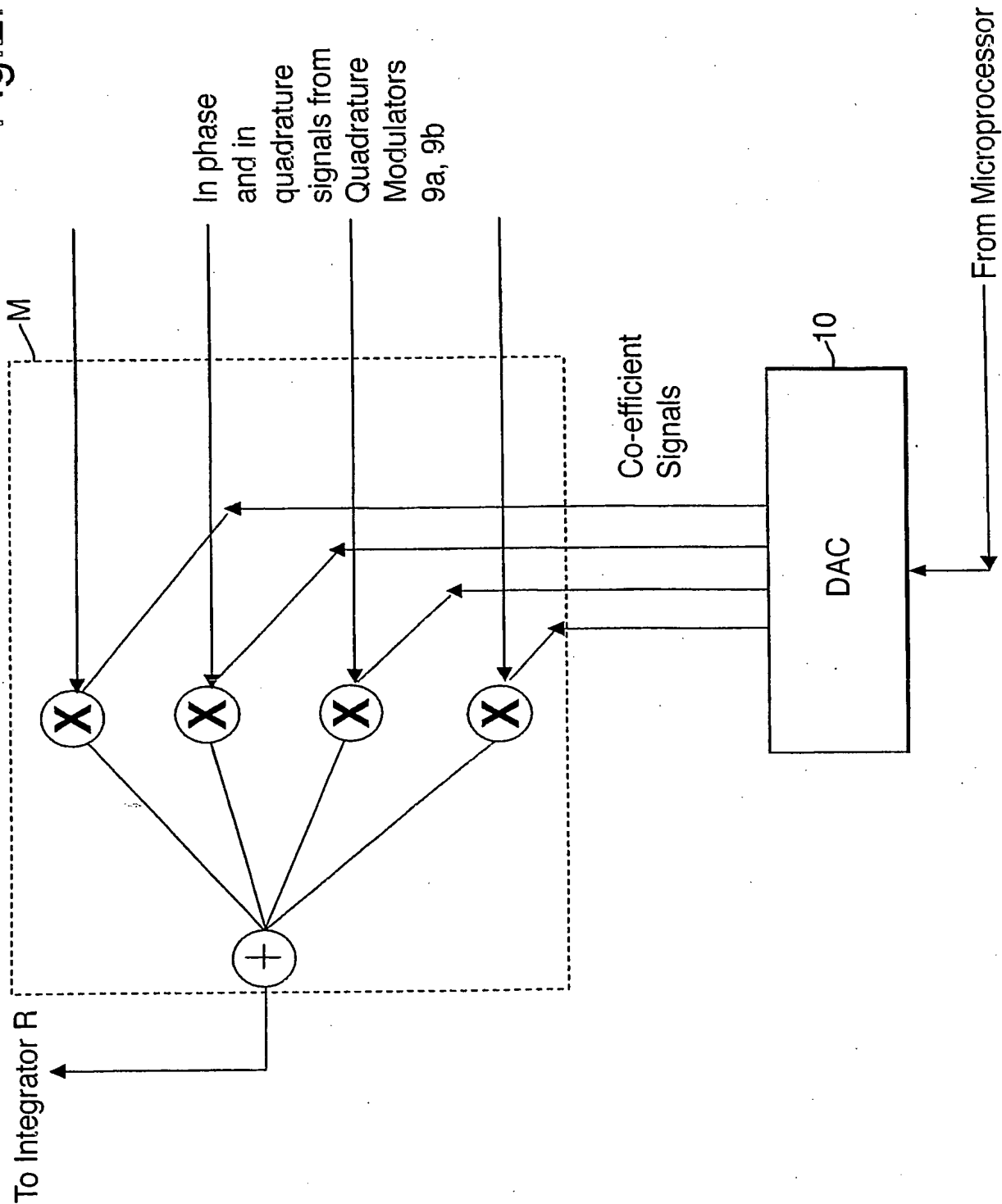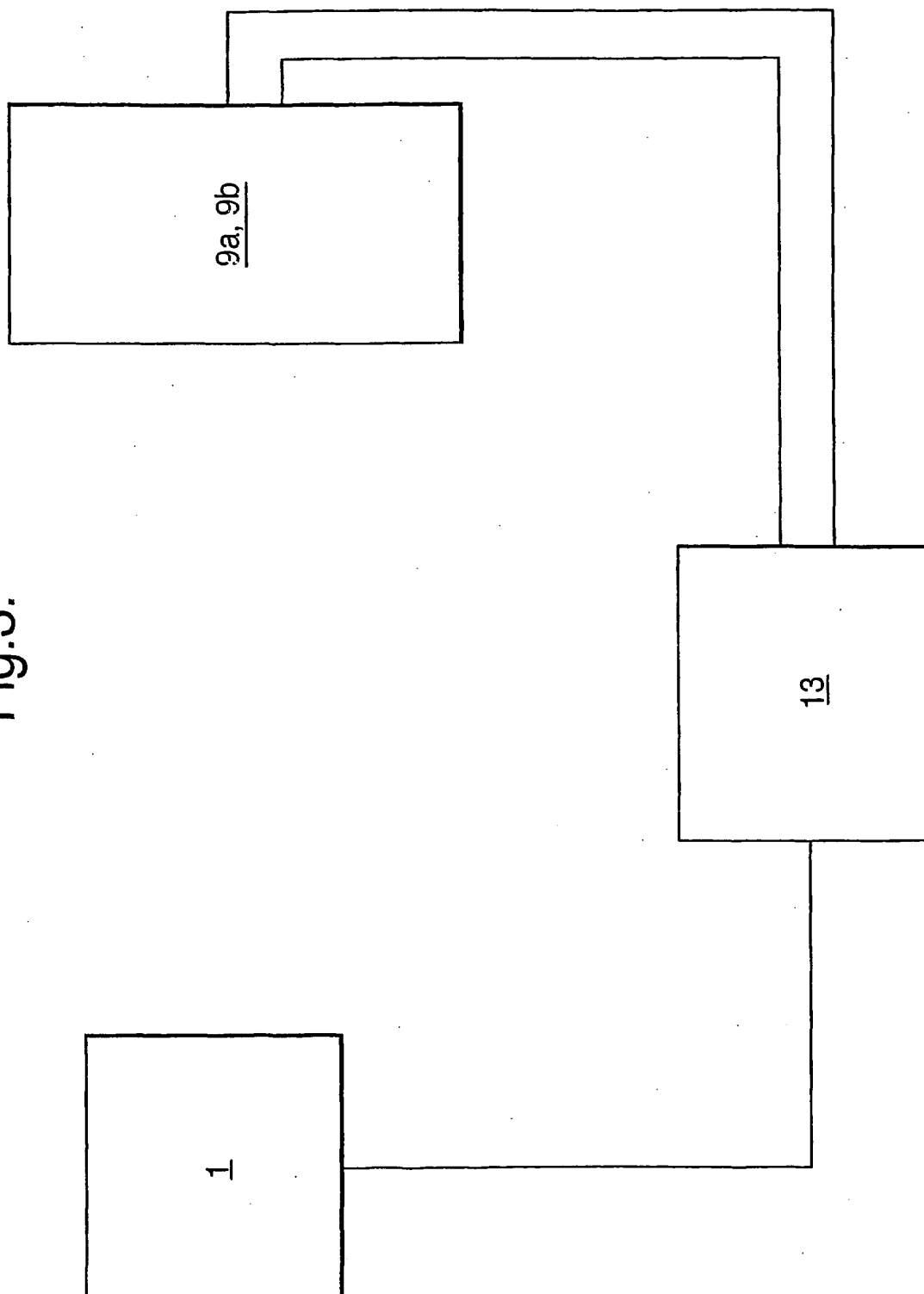
20   immobilised on the surface.

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Fig.1.

Fig.2.

In phase and in quadrature signals from Quadrature Modulators 9a, 9b

From Microprocessor

M

Co-efficient Signals

DAC

10

To Integrator R

Fig.3.

# INTERNATIONAL SEARCH REPORT

**A. CLASSIFICATION OF SUBJECT MATTER**
IPC 7    G01N27/00    H03L5/02

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched  (classification system followed by classification symbols)
IPC 7    G01N    H03L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

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**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

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[X] Further documents are listed in the continuation of box C.     [X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

| Date of the actual completion of the international search | Date of mailing of the international search report |
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| 1 July 2004 | 14/07/2004 |

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**C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT**

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